

DIVISION S-8—NUTRIENT MANAGEMENT & SOIL & PLANT ANALYSIS

Fertigation Frequency for Subsurface Drip-Irrigated Broccoli

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ABSTRACT

Subsurface-drip irrigation and fertigation with fluid N fertilizer sources offers substantial flexibility for N fertilizer management. Fertigation events can be scheduled as often as irrigation, up to several times per day. However, because of system or management constraints very frequent fertigation may not be possible or desirable for some growers. Optimum fertigation interval for subsurface drip-irrigated crops has not been well researched. A 3-yr field experiment was conducted on a sandy loam soil in southern Arizona with subsurface drip-irrigated broccoli (*Brassica oleracea* L. Italica) to i) determine the effects of N rate and fertigation frequency on crop yield, quality, and crop N status, and ii) estimate a N balance. Broccoli was planted in two rows per raised bed 1.02 m apart, with one drip line buried 0.15 to 0.20 m deep within each bed. The experiment included factorial combinations of two N rates and four fertigation frequencies (intervals of 1, 7, 14, and 28 d). Broccoli marketable yield and quality were responsive to N rate, but not to increased fertigation frequency. During one of three seasons, fertigation frequency significantly ($P \leq 0.05$) affected crop N uptake, but there was no trend of increasing N uptake with increasing fertigation frequency. Unaccounted fertilizer N and apparent N use efficiency (ANUE) were calculated for two seasons. Unaccounted fertilizer N averaged 20 and 75 kg ha⁻¹ and ANUE 90 and 81% with 250 and 350 kg N ha⁻¹ applied, respectively. Neither was significantly affected by fertigation frequency. We conclude, therefore, that for broccoli production with subsurface-drip irrigation on sandy loam or finer soils, fertigation can be applied as infrequently as monthly, without compromising crop yield or quality, or causing excessive N losses.

MANY STUDIES have demonstrated drip-irrigated crop response to N (e.g., Bar-Yosef and Sagiv, 1982; Thompson et al., 2002a). Optimum N rates for many drip-irrigated crops have been published (Hochmuth, 1992; Hartz, 1994). Drip irrigation and fertigation with fluid N fertilizer sources offer what is probably the ultimate in flexibility for N fertilizer management. Fertigation events can be scheduled as often as irrigation, up to several times per day. However, because of system or management constraints very frequent fertigation may not be possible or desirable for some growers. Optimum fertigation interval for drip-irrigated crops, although important, has not been thoroughly researched (Hartz, 1994).

Various authors have recommended very frequent or continuous fertigation for drip-irrigated crops (i.e., Bar-

Yosef and Sagiv, 1982; Stark et al., 1983; Burt et al., 1995). However, very few studies have shown a benefit of frequent or continuous fertigation compared with less frequent fertigation. Bar-Yosef and Sagiv (1982) practiced continuous fertigation of surface drip-irrigated tomato (*Lycopersicon esculentum* L.) with concentrations of 100 to 200 mg N L⁻¹ in the irrigation water. However, this resulted in N applications >1000 kg N ha⁻¹, far greater than N uptake by the plants; consequently N use efficiency (NUE) was as low as 30%. Stark et al. (1983) determined that 75 mg N L⁻¹ was the optimum concentration for continuous fertigation of tomato with surface-drip irrigation. Bhella and Wilcox (1985) advocated continuous fertigation of surface drip-irrigated cantaloupe (*Cucumis melo* L.) with 150 and 50 mg N L⁻¹ during vegetative and reproductive stages, respectively.

Few studies are reported in which the effects of different drip-fertigation frequencies on yield and quality of annual crops are compared. Several researchers have compared applications of all N soil-applied preplant with a combination of preplant soil-applied and in-season fertigated N on tomato. Locascio et al. (1985, 1989) found that surface drip-irrigated tomato yields were higher with 40% of the N applied preplant and 60% applied by fertigation, compared with all N applied preplant on sandy soils in Florida. Dangler and Locascio (1990) found that yield of surface drip-irrigated tomato was higher on a fine sand when 50% of fertilizer N was soil-applied before planting, than when all N was applied via fertigation. Cook and Sanders (1991) examined the effect of fertigation frequency (daily to monthly) on subsurface drip-irrigated tomato yields in two South Carolina soils. Daily or weekly fertigation significantly increased yield compared with monthly fertigation, but there was no advantage of daily over weekly fertigation on a loamy sand. The same fertigation frequencies resulted in no differences in yield and quality on a loamy fine sand soil. Locascio and Smajstrla (1995) found that surface drip-irrigated tomato yields with daily fertigation were not increased compared with yields with weekly fertigation on a fine sand. Locascio et al. (1997) found that there were no differences in yield or quality of surface drip-irrigated tomato fertigated either six or 12 times per season. Similarly, yields of surface drip-irrigated pepper (*Capsicum annum* L.) were not affected by fertigation interval (11 or 22 d) on a loamy sand soil (Neary et al., 1995).

Abbreviations: ANUE, apparent N use efficiency; NUE, N use efficiency.

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In summary, while it is often assumed that continuous or daily fertigation is preferable to less frequent fertigation, there is limited evidence in the literature to support this viewpoint, even for drip-irrigated crops grown in sandy soils. Furthermore, in few of the studies cited above were the effects of fertigation frequency on losses of fertilizer N examined (Bar-Yosef and Sagiv, 1982; Stark et al., 1983; Cook and Sanders, 1991). Therefore, studies are needed to determine optimum fertigation frequency, and the effects of fertigation frequency on recovery and loss of fertilizer N.

The objectives of this research were to (i) determine the effects of N rate and fluid N fertigation frequency on crop yield, quality, and in-season N status of a subsurface drip-irrigated broccoli crop, and (ii) estimate a N balance as affected by N rate and fluid N fertigation frequency.

MATERIALS AND METHODS

Three field experiments were conducted during the 1998–2001 winter growing seasons at the University of Arizona Maricopa Agricultural Center (MAC) in a field mapped as a Casa Grande sandy loam soil (reclaimed fine-loamy, mixed, superactive, hyperthermic, Typic Natrigid). Before each cropping season, the experimental area was cropped in the summer with surface flood-irrigated sudangrass [*Sorghum sudanense* (Piper) Stapf] to remove available soil N and reduce field variability. Available soil $\text{NO}_3\text{-N}$ in the surface 0.3 m was $<4 \text{ mg kg}^{-1}$ before broccoli planting each season. Phosphorus (75 kg ha^{-1}) was broadcast as triple superphosphate fertilizer before planting each season, and incorporated into the soil beds. Before broccoli planting, drip irrigation tubing (Twin-wall IV, 0.36-mm wall thickness, 0.23-m emitter spacing delivering $1 \times 10^{-3} \text{ L s}^{-1} \text{ m}^{-1}$ at 70 kPa, Chapin Watermatics, Watertown, NY) was buried 0.15- to 0.20-m deep in north-south oriented, raised soil beds 1.02 m apart and 0.5 m wide at the top. Plot size was 9.1 m long by 4.08 m wide.

'Marathon' broccoli was direct-seeded into dry soil on 8 Oct. 1998, 13 Oct. 1999, and 18 Oct. 2000. Two seedlines per bed (0.25 m apart) were planted using a Stanhay precision planter (Stanhay Webb Co., Suffolk, England). Uniform irrigation was applied through the drip tubing to encourage germination and stand establishment. On stand establishment, plants were thinned to a plant population of 98 000 plants ha^{-1} . Across the three seasons, approximately 290 mm of irrigation water were applied between planting and stand establishment (1–2 true leaf stage).

After stand establishment, daily irrigations were initiated by an automatic controller (Irritrol MC-6, Garden America, Carson City, NV) connected to electronic valves (Ultraflow 700 series, Hardie Irrigation, El Cajon, CA). Irrigation amounts were scheduled based on feedback from tensiometers installed at 0.3-m depth within several plots. Soil water tension was measured in the morning, before daily irrigation, two or more times per week using a Tensicorder (Soil Measurement Systems, Tucson, AZ). The target soil water tension was 8 to 10 kPa (Thompson et al., 2002a), and adjustments in irrigation amounts applied were empirically based on deviation from target tension. Volumes of water applied were monitored by flow meters. Irrigation was applied daily except when rainfall made irrigation unnecessary.

The experiments were randomized complete block factorial designs consisting of combinations of two N rates (200 and 300 kg N ha^{-1} during 1998–1999; 250 and 350 kg N ha^{-1} during

1999–2001) and four fertigation frequencies (fertigation intervals of 1, 7, 14, and 28 d). The experimental design included unfertilized control plots and was replicated four times. All N was applied as urea ammonium nitrate solution (320 g N L^{-1}) injected directly into irrigation water using a Dosatron fertilizer injector (Dosatron Products, Sunnyvale, FL). The plots receiving fertigation at 1-d intervals were fertigated automatically at each irrigation. All other fertilized plots were fertigated manually. All plots, except the unfertilized controls, received an application of 33 kg N ha^{-1} on emergence. Fertigation frequency treatments were commenced following appearance of the first true leaf. The temporal distribution of fertigation for one season is shown in Fig. 1. Daily N uptake rates were based on values reported by Thompson et al. (2002a) for subsurface drip-irrigated broccoli. We assumed a maximum plant N uptake of 4.8 kg ha^{-1} at the first buds growth stage. The low N rate during each season was intended to supply slightly suboptimal N with respect to maximum yield, and the high rate was intended to supply an approximately optimum amount of N (Thompson et al., 2002a).

In each of the three seasons, insects were controlled during early season growth with acephate (O,S-dimethyl acetylphosphoramidothioate, 'Orthene', Valent USA, Walnut Creek, CA) and imidacloprid (1-[6-chloro-3-pyridylmethyl]-N-nitroimidazolidin-2-ylideneamine, 'Admire', Bayer Agricultural Product, Kansas City, MO) at labeled rates. Weed control was accomplished by spraying with glyphosate [N-(phosphonomethyl) glycine, 'Roundup', Monsanto Co., St. Louis, MO] or by handhoeing.

Petioles (10–25) were collected biweekly from each plot beginning at the 4–6 leaf growth stage, dried at 60°C , ground to $<0.6 \text{ mm}$, and extracted and analyzed for $\text{NO}_3\text{-N}$ using an ion-selective electrode (Baker and Thompson, 1992). All aboveground biomass from within 1- m^2 areas in each plot was collected at harvest and divided into head and trim portions. These portions were then dried, weighed, ground to $<0.6 \text{ mm}$, and total N was determined by the micro-Kjeldahl method modified to recover NO_3 (Bremner and Mulvaney, 1982). An error in calibrating the drying oven resulted in destruction of the aboveground biomass samples for the 1998–1999 season, therefore N recovery could not be calculated for this season.

Broccoli heads of marketable size were harvested from a 3- m^2 section of a center bed of each plot. Heads were trimmed to 'U.S. Fancy' specifications for broccoli (USDA, 1943) and individually graded for diameter, weight, discoloration, and hollow stem. Harvest dates were 10 to 22 Feb. 1999, 16 to 23 Feb. 2000, and 5 to 8 Mar. 2001.

Soil samples were collected from each plot as soon as possible after harvest at the end of each growing season using a hydraulic drill rig and a 1.5-m long steel-coring device. Groupings of three adjacent soil cores were taken at distances of 0, 0.25, and 0.50 m from the drip tubing at three randomly selected locations within the harvest area in each plot. Soil samples to a 0.9-m depth were separated into 0- to 0.3-, 0.3- to 0.6-, and 0.6- to 0.9-m depth increments. The nine subsamples from each depth increment were composited within each plot, thoroughly mixed, subsampled, and air-dried and ground to $<2 \text{ mm}$. Analysis of 1 M KCl extractable $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ was performed by steam distillation (Keeney and Nelson, 1982, p. 672–673).

A partial N mass balance was developed for the 1999–2000 and 2000–2001 seasons using the difference method (Bock, 1984). Postharvest unaccounted fertilizer N was calculated as:

$$\text{UN}_i = \text{FN}_i + (\text{WN}_i - \text{WN}_0) - (\text{SN}_i - \text{SN}_0) - (\text{PN}_i - \text{PN}_0) \quad [1]$$

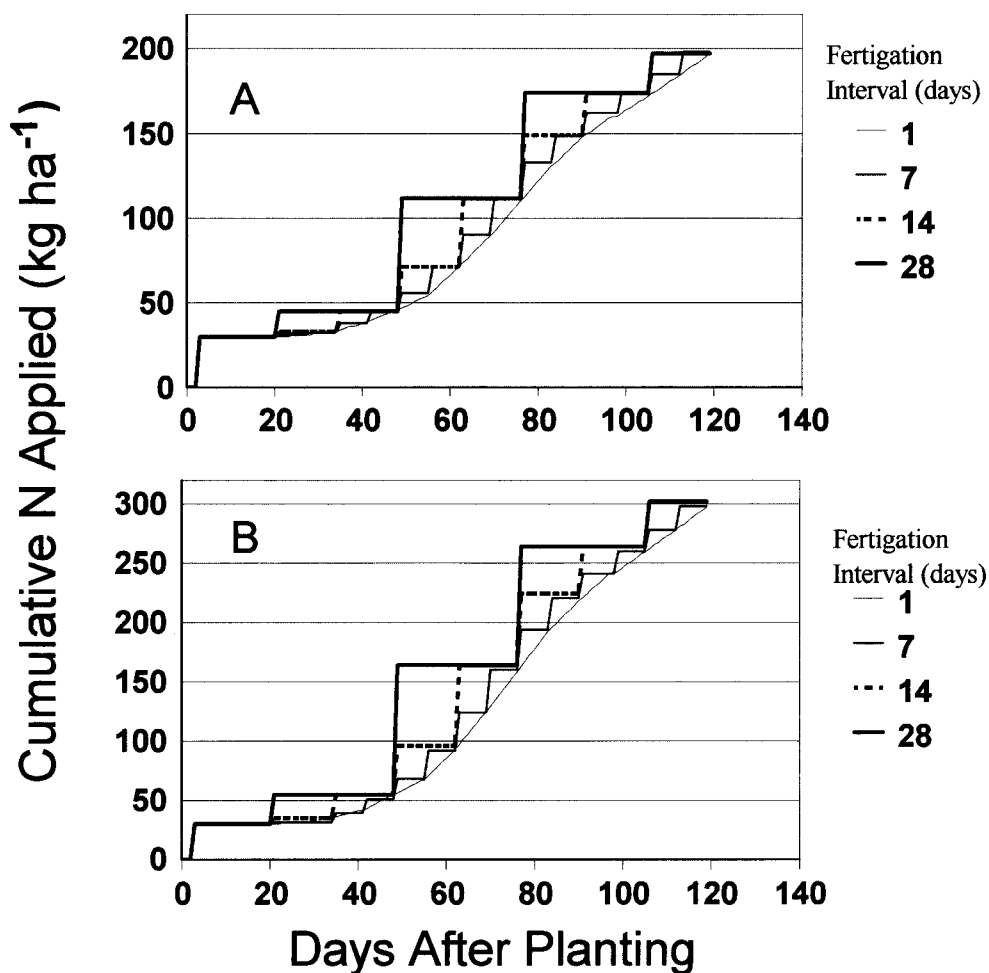


Fig. 1. Cumulative N applications for the different fertigation frequencies applied to broccoli at N rates of (A) 200 and (B) 300 kg N ha⁻¹ for the 1998–1999 winter-growing season.

where UN_i represents unaccounted fertilizer N in plot i , FN_i is fertilizer N applied to plot i , WN_i signifies N applied in irrigation water to plot i ; WN_0 equals N applied in irrigation water to control plots, including water used for stand establishment; SN_i corresponds to the residual soil NH_4-N plus NO_3-N to 0.9-m depth in plot i ; SN_0 accounts for the residual soil NH_4-N plus NO_3-N to 0.9-m depth in control plot harvest areas; PN_i represents the total aboveground crop N uptake in plot i and; PN_0 equals the total aboveground crop N uptake in control plot harvest areas. All equation variables are in units of kilogram per hectare.

The average PN_0 was 23 and 31 kg ha⁻¹ for the 1999–2000 and 2000–2001 growing seasons. These values represent crop N uptake from this field following exhaustive cropping. It was assumed that (i) the fate of indigenous N in control and fertilized plots was the same, and (ii) there was no net change in soil organic matter or microbial biomass N. The entire experimental area was subjected to exhaustive removal of available soil N by multiple harvests of unfertilized sudangrass as well as leaching by several flood irrigation events. This should have resulted in a low potential for soil N mineralization during the broccoli-growing season. Therefore, any differences in N losses observed between fertilized and control plots were assumed to be the result of the treatments or their effects on broccoli growth and N recovery in plant biomass. Average irrigation water NO_3-N was 2.7 mg L⁻¹.

Apparent N use efficiency was calculated as:

$$ANUE = \frac{PN_i - PN_0}{FN_i} \quad [2]$$

Analysis of variance procedures were performed using the SAS statistical procedure PROC GLM (SAS Institute, 1988), and Duncan's Multiple Range Test was used to determine statistically significant differences among means. Because there was no marketable yield in control plots, they were excluded from the analysis of variance procedures. Control plot data, however, were used to calculate fertilizer N recovery in crops and soils.

RESULTS AND DISCUSSION

The first two growing seasons were drier than normal, with rainfall amounts of 11 and 0 mm, respectively, between planting and harvest. Reference crop evapotranspiration (ET_0) as reported by a weather station <100 m from the experimental site was 388 and 403 mm for 1998–1999 and 1999–2000. The last season was wetter and cooler, with 137 mm of rainfall and 318 mm of ET_0 between planting and harvest. Total heat unit accumulations (degree C days) were 899, 955, and 760 for the three seasons. Amounts of irrigation water used after stand establishment were 300, 270, and 260 mm for the three seasons.

Table 1. Analysis of variance summary for marketable yield, head weight and diameter, N uptake, residual soil N, unaccounted fertilizer N, and apparent N use efficiency (ANUE) as affected by N rate (N) and fertigation frequency (Freq).

Season	Source	df	Marketable yield	Head weight	Head diameter	N uptake heads†	N uptake trim	N uptake total	Residual soil N	Unaccounted N	ANUE
1998-1999	Replication	3	NS‡	NS	NS	–	–	–	NS	–	–
	N	1	**	*	NS	–	–	–	*	–	–
	Freq	3	NS	NS	NS	–	–	–	NS	–	–
	N × Freq	3	NS	NS	NS	–	–	–	NS	–	–
	Error	16									
	CV %		24.6	13.1	6.1	–	–	–	12.0	–	–
1999-2000	Replication	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	N	1	NS	NS	NS	**	**	**	NS	**	**
	Freq	3	NS	NS	NS	*	**	**	NS	NS	**
	N × Freq	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Error	21									
	CV %		9.8	7.9	3.3	9.6	11.7	8.6	23.1	82.4	9.5
2000-2001	Replication	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	N	1	**	**	**	*	**	**	NS	**	*
	Freq	3	NS	NS	**	NS	NS	NS	NS	NS	NS
	N × Freq	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Error	21									
	CV %		12.1	10.7	4.4	17.8	18.5	15.0	14.6	72.5	16.0

* Significant at $p \leq 0.05$.

** Significant at $p \leq 0.01$.

† Plant N uptake, unaccounted N, and ANUE could not be calculated for the 1998-1999 season.

‡ NS, not significant.

Table 2. Broccoli marketable yield and head weight and head diameter, 1998-2001.

Season	N rate	Fertigation frequency	Marketable yield	Head weight	Head diameter
	kg ha ⁻¹	d	Mg ha ⁻¹	kg	cm
1998-1999	200	1	11.3	0.113	8.6
		7	11.3	0.113	8.7
		14	11.4	0.117	9.0
		28	10.7	0.110	8.7
		DMRT†	NS	NS	NS
	300	1	13.6	0.128	9.1
		7	12.2	0.113	8.3
		14	12.8	0.145	9.8
		28	12.6	0.127	8.9
		DMRT	NS	NS	NS
1999-2000	250	1	19.1	0.185	11.2
		7	20.0	0.178	11.0
		14	20.6	0.180	11.0
		28	18.5	0.165	10.8
		DMRT	NS	NS	NS
	350	1	20.5	0.180	11.1
		7	22.7	0.193	11.4
		14	19.2	0.185	11.2
		28	18.9	0.188	11.2
		DMRT	NS	NS	NS
2000-2001	250	1	19.4	0.175	10.8
		7	19.2	0.173	10.8
		14	17.6	0.175	11.1
		28	20.8	0.195	11.6
		DMRT	NS	NS	NS
	350	1	20.0	0.193	11.3
		7	22.2	0.220	11.8
		14	23.3	0.210	11.2
		28	22.3	0.210	12.2
		DMRT	NS	NS	0.6

† Critical values ($P = 0.05$) from Duncan's Multiple Range Test for pairwise comparisons of fertigation frequency means within a season and N rate. NS = not significant.

During the 1998–1999 and 2000–2001 seasons, the high N rate significantly ($P \leq 0.05$) increased marketable yield and quality (head weight in 1998–1999; head weight and diameter in 2000–2001) compared with the low N rate (Tables 1 and 2). During the 1999–2000 season, however, there was no significant effect of N rate on marketable yield or quality. Overall, yield and quality were excellent, particularly during the 1999–2000 and 2000–2001 seasons. Thompson et al. (2002a) also reported a positive response of subsurface drip-irrigated

broccoli yield and quality to increasing N rate, and found that marketable yields were maximized at N rates of 350 to 450 kg N ha⁻¹. There were few statistically significant effects of fertigation frequency on yield or quality. During 2000–2001, the longest fertigation interval (28 d) resulted in the greatest head diameter (Table 2). Head diameter is a significant quality factor for fresh-market broccoli. During 1999–2000, in the high N rate treatments, plots fertigated weekly had higher marketable yield than plots fertigated every 14 or 28 d.

Petiole $\text{NO}_3\text{-N}$ concentrations (Fig. 2) support the assumption that there was little difference in N status among plots receiving the different fertigation frequencies. Nitrogen rate significantly ($P \leq 0.05$) affected petiole $\text{NO}_3\text{-N}$ on 15 of 18 sampling dates during the three seasons, while fertigation frequency was significant only for 8 of the 18 sampling dates. There were few consistent trends of petiole NO_3 concentrations with respect to fertigation frequency. However, in 5 of 6 possible comparisons, petiole $\text{NO}_3\text{-N}$ concentrations in plants fertigated every 28 d were significantly lower than those fertigated more frequently at the first sampling date (Fig. 2). However, there is no evidence that this negatively affected yield or quality. With both N rates, peti-

ole $\text{NO}_3\text{-N}$ concentrations were below published critical levels (Doerge et al., 1991; Hartz, 1994) for significant portions of the first two seasons. Thus, a higher rate of N applied preplant or at planting may have been beneficial during these seasons. Low petiole $\text{NO}_3\text{-N}$ concentrations during the early part of the growing season might enhance any potential benefits of increased fertigation frequency. The lack of any such benefit suggests that fertigation frequency was not a critical management variable under the conditions of this experiment.

These results suggest that, for subsurface drip-irrigated broccoli grown in a sandy loam or similar soil texture, fertigation frequency is not a critical manage-

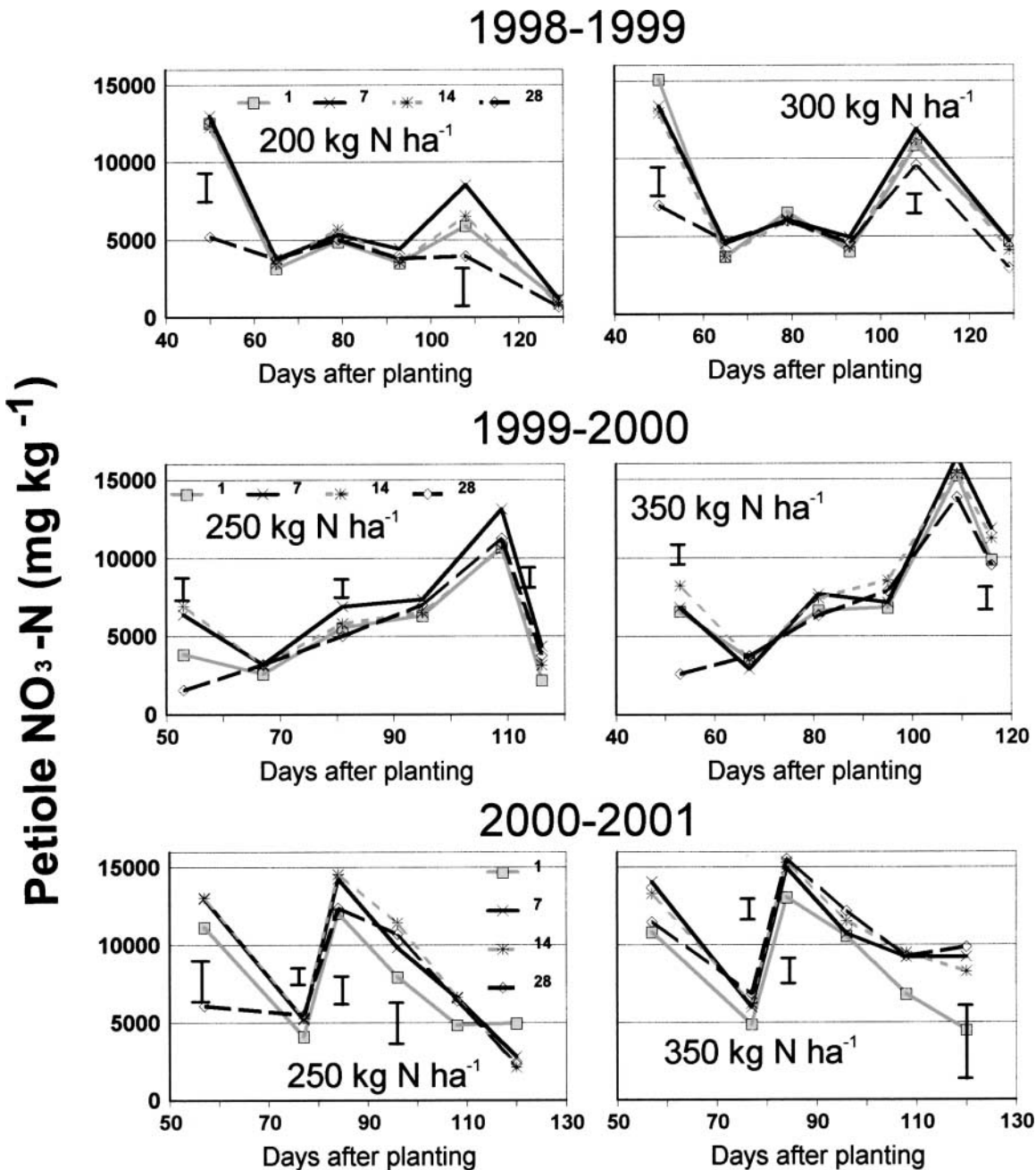


Fig. 2. Petiole $\text{NO}_3\text{-N}$ concentrations during the 1998–2001 winter growing seasons as affected by N rate, fertigation frequency, and days after planting. Error bars, where shown, indicate significant differences ($P \leq 0.05$) according to Duncan's Multiple Range Test.

ment variable affecting crop yield and quality. This could be an important consideration for growers who do not have the ability, because of system or management limitations, to fertigate continuously. These results are in general agreement with results reported by several other researchers. For example, Neary et al. (1995) found no advantage of fertigation at 11-d intervals compared with 22-d intervals for surface drip-irrigated pepper grown on a loamy sand. Dangler and Locascio (1990) found that variations in fertigation amount applied on a weekly basis did not affect yield or quality of surface drip-irrigated tomato grown on a fine sand. Locascio and Smajstrla (1995) reported that tomato yield and quality were not significantly different when N was fertigated daily or weekly via a surface drip system. Cook and Sanders (1991) found that marketable yield and fruit size of subsurface drip-irrigated tomato were significantly higher with daily compared with biweekly or monthly fertigation on a loamy sand soil, but that yield and quality were unaffected by variations in fertigation frequency on a loamy fine sand.

Crop response to fertigation frequency is likely a function of soil texture and irrigation management. Crops grown in coarse-textured soils, or crops grown during summer growing seasons, when higher amounts of water are applied, may benefit most from frequent, as opposed to infrequent, fertigation. In general, those studies cited above support this hypothesis. Positive crop response to frequent fertigation is most often seen in very coarse-textured soils (e.g., Cook and Sanders, 1991), and a lack

of crop response to frequent fertigation is more common when soils are finer than loamy sand (e.g., Cook and Sanders, 1991; Locascio et al., 1997). The influence of soil texture is very likely that (i) soil clay content will largely determine cation-exchange capacity and hence nutrient-holding capacity, and (ii) rates of water and nutrient leaching are usually higher in coarse-textured than in fine-textured soils. Cook and Sanders (1991) observed that NO₃-N concentrations within subsurface drip-irrigated vegetable beds were higher throughout a tomato growing season in a loamy fine sand compared with a loamy sand, when both received equal amounts of N by fertigation.

Nitrogen uptake in heads and trim was significantly ($P \leq 0.05$) affected by N rate and fertigation frequency during 1999–2000 (Table 1). The effect of fertigation frequency was significant only within the low N rate. With 250 kg N ha⁻¹ applied, N uptake in the heads was significantly higher with weekly than with biweekly fertigation (Table 3). Nitrogen uptake in trim and total N uptake were significantly higher with daily fertigation than with biweekly fertigation. Other differences were not significantly different. With 350 kg N ha⁻¹ applied, there were no significant differences among fertigation frequencies, although N uptake in trim and total N uptake tended to be higher with more frequent fertigation. During 2000–2001, N rate significantly affected N uptake in heads and trim, but these were unaffected by fertigation frequency (Table 1). Nitrogen removal in the heads was as high as 127 kg N ha⁻¹, and total aboveground N

Table 3. Nitrogen recovery in broccoli plants, residual soil NH₄⁺ plus NO₃⁻, unaccounted fertilizer N, and apparent N use efficiency (ANUE) for broccoli, 1998-2001.

Season	N rate	Fertigation frequency	N in heads [†]	N in trim	Total biomass N	Residual soil N	Unaccounted fertilizer N	ANUE		
	kg ha ⁻¹	d	kg ha ⁻¹					%		
1998-1999	200	1	–	–	–	167	–	–		
		7	–	–	–	157	–	–		
		14	–	–	–	152	–	–		
		28	–	–	–	159	–	–		
	DMRT‡	300	1	–	–	–	NS	–	–	
			7	–	–	–	160	–	–	
			14	–	–	–	202	–	–	
			28	–	–	–	159	–	–	
	1999-2000	DMRT	250	1	112	165	276	66	–3	101
				7	116	151	266	77	–4	97
				14	99	131	230	73	37	83
				28	108	138	246	84	10	89
DMRT		350	1	16	27	34	NS	NS	13	
			7	120	183	304	74	62	80	
			14	131	181	312	88	42	82	
			28	112	158	270	80	91	70	
2000-2001		DMRT	250	1	121	156	277	90	74	73
				7	NS	NS	NS	NS	NS	NS
				14	104	157	261	15	17	92
				28	102	138	240	14	42	84
	DMRT	350	1	106	127	233	15	45	81	
			7	112	142	254	15	26	89	
			14	112	142	254	15	26	89	
			28	112	142	254	15	26	89	
	DMRT	350	1	NS	NS	NS	NS	NS	NS	
			7	118	161	279	15	98	71	
			14	123	188	311	15	69	80	
			28	116	168	284	13	98	72	
			127	185	312	14	69	80		
			NS	NS	NS	NS	NS	NS		

[†] Plant N uptake, unaccounted N, and ANUE could not be calculated for the 1998-1999 season.

[‡] Critical values ($P = 0.05$) from Duncan's Multiple Range Test for pairwise comparisons of fertigation frequency means within a season and N rate. NS = not significant.

Soil NO₃-N (mg kg⁻¹)

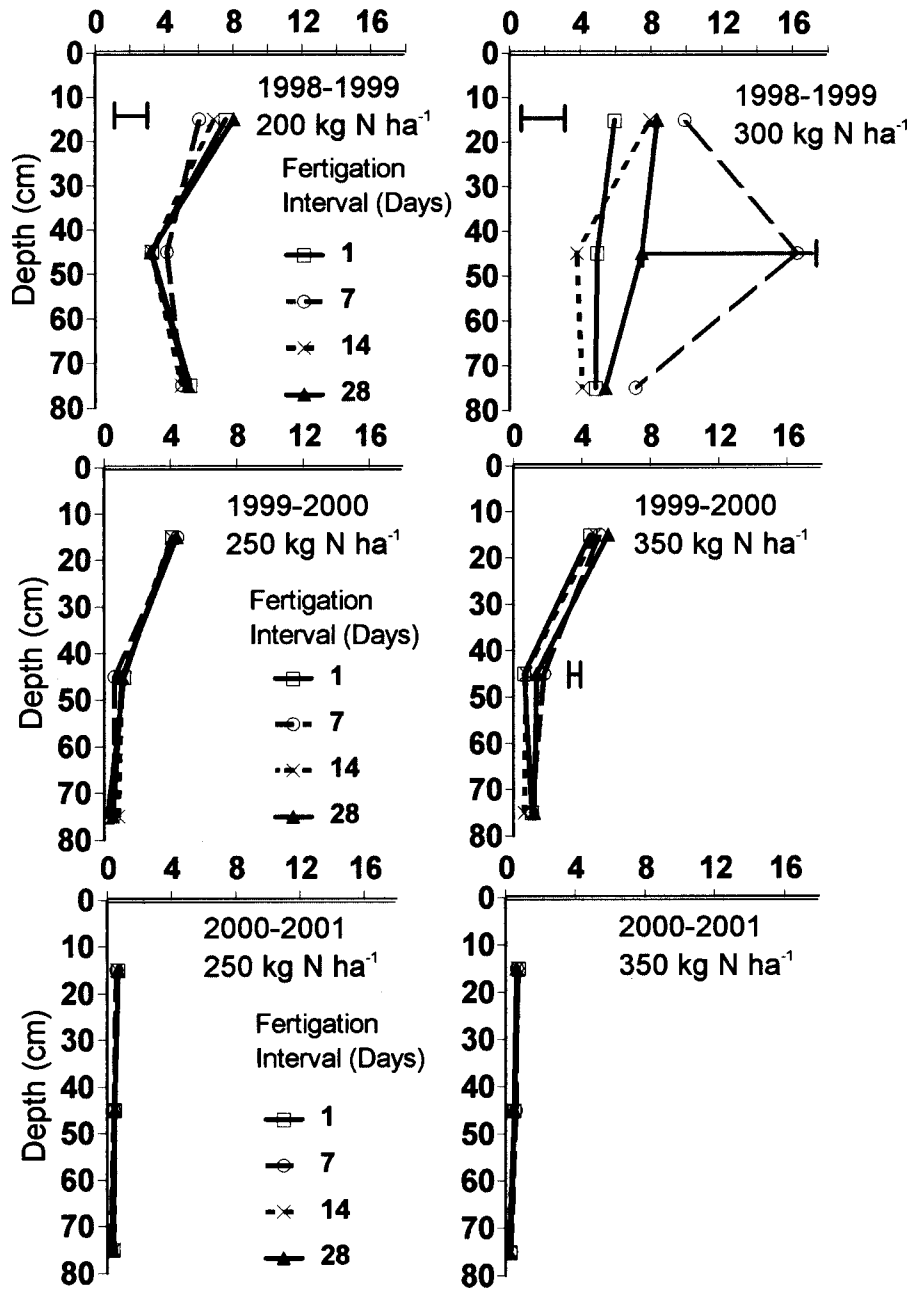


Fig. 3. Postharvest residual soil NO₃-N concentrations for broccoli during the 1998-2001 winter growing seasons. Error bars, where shown, indicate significant differences ($P \leq 0.05$) according to Duncan's Multiple Range Test.

uptake was as high as 312 kg N ha⁻¹. Nitrogen uptake was high, compared with values previously reported for Arizona (Doerge et al., 1991; Thompson et al., 2002a).

Very few researchers have evaluated the effects of fertigation frequency on measurements of environmental significance, such as residual soil NO₃, NUE, or unaccounted fertilizer N. Such measurements can indicate directly or indirectly the relative effects of fertigation treatments on N losses from cropping systems. Bar-Yosef and Sagiv (1982) practiced continuous fertigation of surface drip-irrigated tomato on sandy soils; however

they reported NUE values as low as 30%. Stark et al. (1983) also applied N by continuous fertigation to surface drip-irrigated tomato. However, they reported NUE of >60% even with 600 kg N ha⁻¹ applied. Cook and Sanders (1991) reported that when equal amounts of N were applied via fertigation, soil NO₃-N concentrations were higher throughout a growing season in a loamy fine sand compared with a loamy sand soil.

In the current study, we measured residual soil N, unaccounted fertilizer N, and ANUE to evaluate N losses from the soil-plant system. Residual soil N was

highest during 1998–1999, and lowest during 2000–2001 (Table 3). During 1998–1999, residual soil N was significantly affected by N rate (Table 1), and was highest at the high N rate (Fig. 3). During 1999–2000 $\text{NO}_3\text{-N}$ concentrations in soil (Fig. 3) were lower than during 1998–1999, and soil N recovery was unaffected by N rate (Table 1). During 2000–2001, soil N concentrations (Fig. 3), and recoveries (Table 3) were lower still, and were unaffected by N rate. Fertigation frequency did not affect residual soil N during any season, or at any N rate (Table 1).

The striking differences in residual soil N among seasons were likely related to two factors. First, marketable yields during 1998–1999 were approximately one-third less than yields during the subsequent two seasons. This probably resulted in less plant N uptake. Unfortunately, an error in calibrating a drying oven resulted in destruction of the plant samples from 1998–1999, so this assumption cannot be confirmed. Another reason for the difference among the seasons may be the difference in rainfall distribution. The 1998–1999 season was uniformly dry, with only 11 mm of rainfall, and no rainfall fell between harvest and soil sampling. During the 1999–2000 season, no rain fell between planting and harvest, but 46 mm of rain fell during a 3-d period shortly after harvest, before soil samples could be collected. During 2000–2001, 137 mm of rain fell between planting and harvest, with 27 mm falling after the last N application, and before soil sampling. These rain events may have leached substantial N below the depth of sampling (0.9 m) and could have contributed to the low residual soil N during the final two seasons.

Unaccounted fertilizer N was calculated for the 1999–2000 and 2000–2001 seasons by accounting for (i) additions of N by fertilizer and irrigation water and by soil N mineralization as estimated by control plot plant N uptake, and (ii) recovery of N in plant biomass and as residual soil N. All other N was assumed to be lost from the system. Unaccounted fertilizer N was significantly affected by N rate during each of the final two seasons, but was not affected by fertigation frequency (Table 1). Across the final two seasons, unaccounted fertilizer N averaged 20 and 75 kg ha^{-1} for the low and high N rates, respectively (Table 3). Thompson et al. (2002b) reported unaccounted N of 20 to 80 kg N ha^{-1} for subsurface drip-irrigated broccoli receiving similar N rate applications as in the current study.

Apparent N use efficiency was significantly affected by both N rate and fertigation frequency during the 1999–2000 season (Table 1). During this season, NUE was significantly higher at the low N compared with the high N rate. Within the low N rate treatments, ANUE was significantly higher with daily compared with bi-weekly fertigation. Within the high N rate treatments, there were no significant differences in ANUE among fertigation frequencies (Table 3). During 2000–2001, ANUE was significantly affected by N rate, but not by fertigation frequency (Table 1). When averaged across the final 2 yr of the experiment, ANUE was 90% with 250 kg N ha^{-1} applied, and 81% with 350 kg N ha^{-1} applied. By any realistic standard, these are very high

values for NUE, illustrating the high potential efficiency of fertigation through subsurface drip-irrigation systems, even with fertigation applied no more than every 28 d.

CONCLUSIONS

Nitrogen was applied by fertigation daily, weekly, biweekly, or monthly to subsurface drip-irrigated broccoli at two N application rates on a sandy loam soil in southern Arizona. Broccoli yield and quality were significantly affected by N rate but there were almost no significant effects of fertigation frequency. Similarly, differences in fertigation frequency resulted in almost no significant differences in residual soil N, unaccounted fertilizer N, or ANUE. Nitrogen use efficiency was high ($\geq 70\%$) regardless of fertigation frequency. We conclude that, provided growers manage irrigation properly, and use appropriate amounts of N, high-frequency fertigation is not an important management variable for subsurface drip-irrigated broccoli grown on sandy loam or finer soil textures. It is reasonable to assume, however, that more frequent fertigation may be needed for broccoli grown on very coarse-textured soils, or for other crops that receive much higher amounts of irrigation water (i.e., summer-grown crops).

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